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AN EXTENSION OF THE COMBINATORIAL GEOMETRY TECHNIQUE FOR MODELING VEGETATION AND TERRAIN FEATURES

Prepared by

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June 1974

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An extended version of the MAGI Combinatorial Geometry technique has been developed which is capable of realistic modeling of trees and bushes. The method has been demonstrated photographically using the SYNTHAVISION process developed by MAGI. Although the basic modeling techniques are those of the standard Combinatorial Geometry method, major extensions have been introduced to reduce the strains on computer memory and computer time that are inherent in a complex description. The method will eventually be capable of integrating the

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tree and bush model with models of terrain features, camouflage nets and BRL-COMGEOM descriptions of vehicles. These features of the program are in progress but not yet complete.

FOREWORD

The work described in this report is part of the AMC Target Signature Analysis Program (formerly Ground Target Signature Program), whose objective is to unify target signature methodology within the Army by developing predictive and empirical models of the fundamental physical phenomena associated with ground target and background signatures in the optical spectrum, and to apply these signatures to the design and evaluation of surveillance systems, weapon guidance systems and countermeasures. Much of the modeling in this program is related to the Combinatorial Geometry (COMGEOM) technique, originally developed by Mathematical Applications Group, Inc. (MAGI), for generating computerized descriptions of three dimensional objects. This report describes an extension of this technique to vegetation and terrain feature modeling.

Terrain and vegetation models are integral parts of the total Target Signature Analysis Program. When all elemental models are complete they will be combined into system performance models to aid in weapon system and camouflage design and evaluation. This involves defining a geographical area in terms of terrain and vegetation (this report), placing vehicles on the terrain and within the surround, illuminating them with natural and artificial sources, exercising them and generating their emissive and reflective signatures, camouflaging them or leaving them unmodified, and then simulating surveillance, target acquisition and terminal homing situations.

It is anticipated that these models will aid in the design and development of a broad range of military equipments and systems, including smart mines, terminal homing seekers, and camouflage material. There have been spin-offs in these directions already, and more are anticipated as the program progresses.

LAWRENCE J. VANDE KIEFT
Chairman
TSA Steering Committee

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I. INTRODUCTION

The goal of this contract was to produce an extended version of the MAGI Combinatorial Geometry technique[1] capable of efficient and realistic modeling of vegetation and other terrain features. In support of this goal a plan was evolved which included the following areas:

A. A survey of existing data on vegetation forms to guide the construction of the statistical tree model.

B. Development of input forms and selection techniques reflecting the results of the data survey.

C. Development of a statistical model of a tree (or bush) using a small number of prototype components which can be located in their own coordinate systems by means of a multi-stage tracking technique. The prototype approach conserves memory while the multi-stage method conserves time.

D. Development of the tracking techniques required by the prototype-multi-stage environment.

E. Development of a module for selection of ray origins, specifically one that is consistent with the photographic demonstration of the model.

F. Implementation and testing of an adaptation of the camouflage net technique to simulate terrain features, i.e. rocks or boulders and hilly terrain.

G. Development of a driver program to govern the input, source selection, internal modeling, tracking and ultimate scoring of the results. In addition this program must provide for reading and processing non-vegetation inputs (such as BRL COMGEOM[2] vehicle descriptions, camouflage nets and terrain models) and casting these in a form comppatible with the new tracking techniques.

All of these goals have been addressed and most of them have been implemented to produce an experimental program. The program has been used to produce pictures of a coniferous tree and a deciduous tree, which are shown in Section VII.

Efforts which at this stage are incomplete are the input processor for the tree and one aspect of the driver program, namely, the reading and processing of non-vegetation inputs. Both efforts are in the programming stage. In addition the adaptation of the camouflage net technique to represent terrain

requires the testing of color patterns and of selected sets of geometry input parameters. This effort has been planned but not executed.

The various aspects of the model will be developed in Sections II through VI. Results will be presented in Section VII. In Section VIII, those areas requiring improvement will be identified and possible methods will be outlined.

II. THE PROTOTYPE-MULTI-STAGE COMBINATORIAL GEOMETRY MODEL

The entire effort reported here has been dominated by the enormous complexity of the objects to be modeled and the potential demands that such complexity would make on computer memory and running time. It was in response to the storage problem that the use of prototypes was introduced. An attempt has been made to meet the need for greater efficiency in ray tracing by means of the multi-stage method.

In addition to meeting the specific needs of the vegetation model, the prototype-multi-stage method can be used to integrate different types of descriptions, each with its own ray tracing techniques, into a single complex scene.

A. The Prototype

A prototype is, for our purposes, a combinatorial geometry model of some sub-structure of a scene. It is constructed in its own coordinate system and ray tracing takes place in that coordinate system. The prototype may have in its description references to both real regions and other prototypes.

A reference to a prototype in another description is made by means of the prototype "copy". The copy exists in the coordinate system of the other description and consists of a box denoting the volume occupied by the copy. A pointer-signal leads to the right prototype and to the right ray tracing techniques and transformation data so that a ray that strikes the copy can be placed at the right position and in the right attitude for ray tracing in the prototype. The presently allowed transformations consist of a displacement, three rigid rotations and a magnification.

It should be observed that the amount of copy data is small - about equal to that required to describe a two-body structure. Thus, if the prototype is copied many times, there is a considerable saving in storage over that required for the "in-place" descriptions.

Another use of the prototype is based on convenience: a structure that has been described for some other scene can be used without change by specifying a position, rotations and scale change for the current scene. The structure can be enclosed in a simple body (e.g. the RPP) and a copy of this (a box) is obtained in the right location, size and orientation in the laboratory system by transformation of the RPP. The pointer-signal and the transformation stored with the copy gives access to the prototype to a ray striking the copy in the laboratory system.

Some of these ideas are illustrated in Figure 1 where a prototype (complex structure) is described in the u,v,w coordinate system and is enclosed by an RPP. The copies (1 and 2) in the real world (x,y,z coordinate system) are boxes obtained

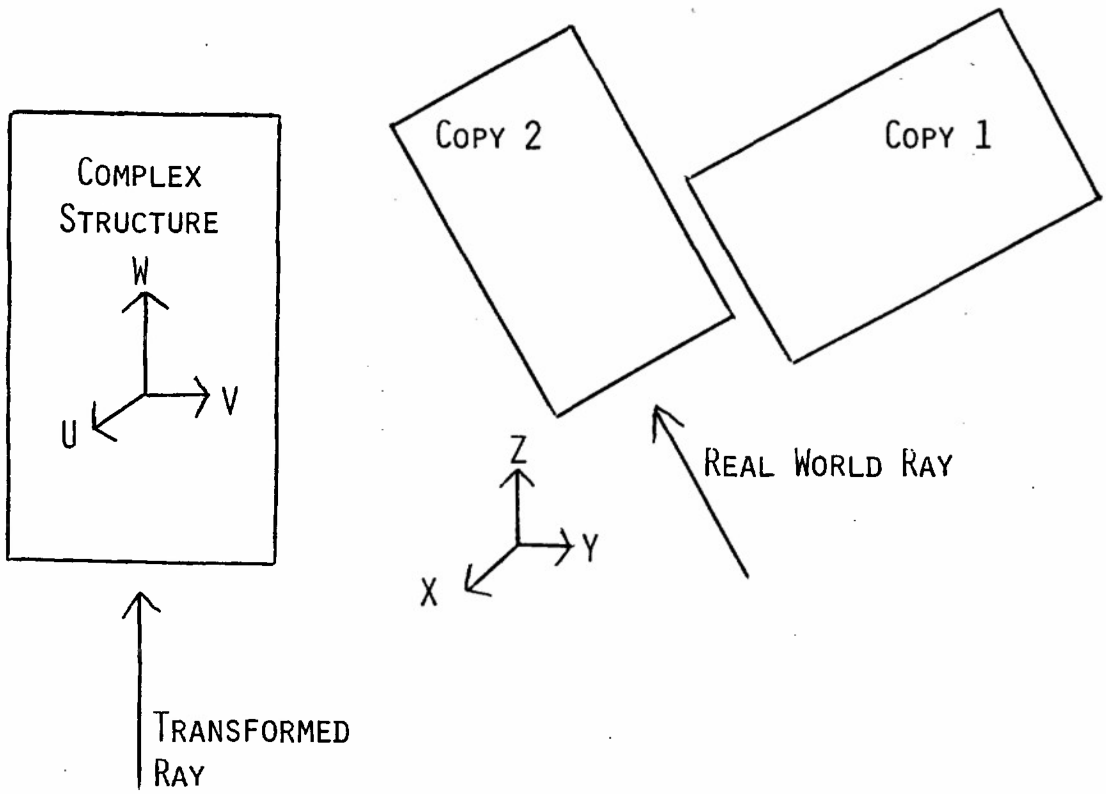


FIGURE 1: THE PROTOTYPE AND THE COPY

by means of two different transformations. A ray striking copy 2 undergoes the inverse transformation and the "interior" of the copy is investigated in the u,v,w system.

The use of this method in integrating different kinds of descriptions, each of which has special ray tracing techniques associated with it, is illustrated in Figure 2. A "real world" boundary - region 20 - encloses all the elements of the scene. Among the data stored with the description of region 20 is a pointer-signal indicating that there are interior regions - which may overlap. This informs the code that a certain kind of tracking is required and also points to the location of the list of interior regions, namely 15, 16 and 17. In this case there is no transformation data to be stored.

Developing this last idea a bit further, it can be seen that, for problems involving vast storage, the regions 15, 16 and 17 provide a natural sorting into geometry bands. Each ray striking region 15 (which contains a BRL-COMGEOM tank description) can be described in one file by ray number, distance to the surface of region 15 from the source point and the direction of the ray and this file becomes a source for an overlay in which standard combinatorial geometry tracking is performed for the tank. For region 16 the overlay can perform tracking in the mode appropriate to the vegetation model, while the overlay invoked for region 17 performs the specialized camouflage net tracking.

The prototype concept is a simple example of the multi-stage concept: complex portions of the scene are represented in the real world by simple outlines. The interior is only investigated if the ray strikes the outline.

B. The Multi-Stage Concept

A multi-stage description is a layered description of space in which each successive layer contains a more detailed description of a given volume. The more detailed description of the next level is investigated only if the containing body of the current stage is struck by the ray. Since the computer time involved in ray tracing is roughly proportional to the number of bodies that must be investigated, the layered description can reduce computer time by limiting the number of bodies to which the ray is exposed.

A special tracking system together with a signal-pointer-storage system has been devised for tracking in this environment. The basic idea is that a region struck in one level of tracking may have "interior" regions belonging to the next level of tracking and connected with the containing region via transformation data (which may be an identity transformation). The signal is stored with the external region data and consists of a positive or negative number whose absolute value, if not zero (or other special positive values), is a pointer to an array defining the interior structure of the region. The sign of the pointer is used to choose between standard tracking (for input models) and the new tracking described here. A zero value of the pointer indicates that this

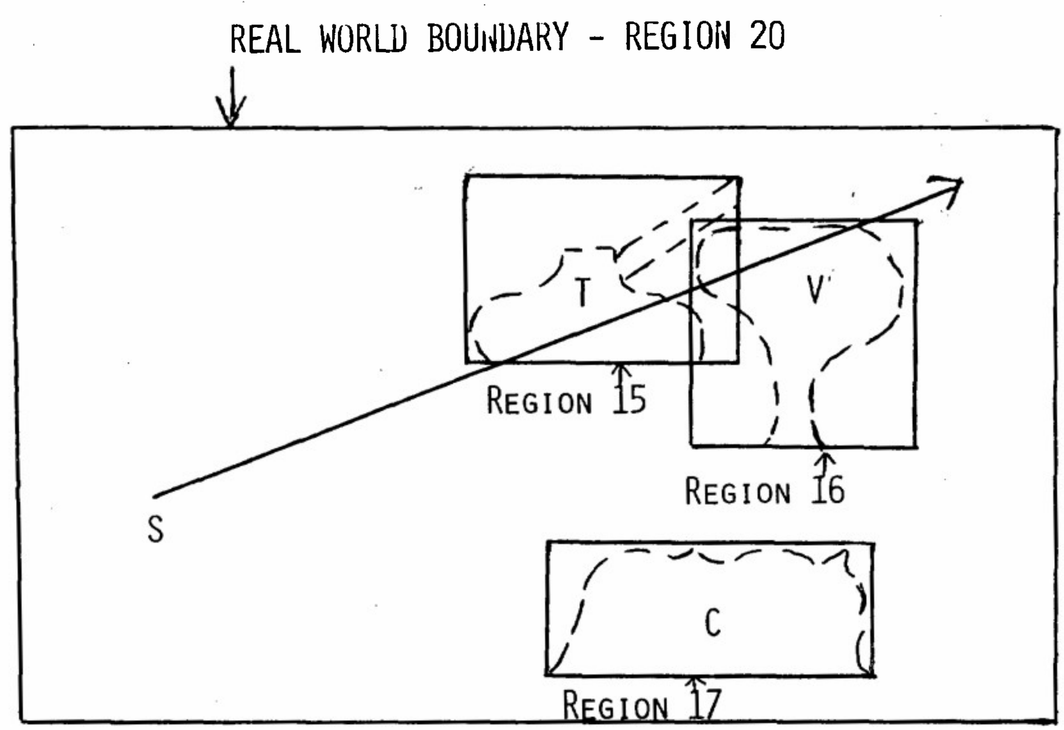


FIGURE 2: USE OF THE PROTOTYPE-MULTI-STAGE METHOD TO INTEGRATE DIFFERENT MODELS IN A SINGLE SCENE

is a "real" region as opposed to a mathematical region with internal structure.

"Internal" regions, which themselves have structure, may overlap, and for this reason a code system must be available to track to each of a set of named regions as opposed to standard tracking to the "next" region whose identity is to be determined.

A conceptual tracking path is a stack of regions, each internal to the preceding, the stack terminating in a real region and yielding a distance along the ray. This path may be varied at any level by choosing another of the internal regions at that level. The choice among paths is made on the basis of shortest distance to a real object.

It can be demonstrated that the optimum number of internal regions is small. Consider a system described by N simple (one-body) regions. Let the number of internal regions per external region be n and the number of levels of description be L. If all real bodies are in the last level of description then

$$N = n^L = \text{constant}$$

and the minimum number of regions tracked to is $n \cdot L$. This minimum corresponds to the happy circumstance of striking only one region per level.

If we minimize the quantity $n \cdot L$ subject to the condition that N is constant we find that n is 3.

In a dense system such as a tree the probability of striking more than one region per level is very high. If, on the average, two of the hypothetical three regions per level are struck, then the ray can be exposed to as many as 2^L times as many regions as the minimum. This can easily obviate the advantage of the multi-stage concept and suggests that some ordering of regions along the ray is desirable. Referring again to Figure 2 where the ray strikes regions 15 and 16 in order, an initial investigation of region 15 will more often than not terminate the ray within 15 and the investigation of region 16 becomes unnecessary.

In addition to the ordering of regions, a reduction of unnecessary overlap is desirable. If the ray of Figure 2 strikes something in region 15 within the overlap region, then region 16 must also be probed for a closer strike.

These ideas will be discussed further in the section on results. In Chapter III, the application of these techniques to the tree model will be described.

III. THE TREE AND BUSH MODEL

In its current experimental version the tree model consists of seven levels of description, five of which act as prototypes for other levels. The other two consist of rectangular parallelepipeds used for reducing the complexity of the description for ray tracing.

The philosophy underlying the construction can be seen in Figure 3 where a tree stem and one primary branch are shown. The tree is assumed to consist of a stem and primary branches. The primary branch has a stem-like structure from which secondary branches emanate. The secondary branches have stems topped by a leaf and twig structure. The basic prototypes of the tree are the twig and leaf structure, the secondary branch, the segment of a primary branch, the primary branch and, finally, the tree itself. The full tree is a prototype for a complete scene.

The leaf and twig structure has a digitized description which will be discussed fully in the next chapter.

The secondary branch is shown in Figure 4, where a truncated right cone (the TRC of the standard combinatorial geometry package) acts as a stem for the RPP representing a copy of the leaf and twig structure. The center of the base of the TRC is always located at the origin and the base radius is unity. The height is deduced from input and the upper radius is determined from the resident taper function which will be given in the chapter on data. Also given by input is a set of numbers which determine the proper match for the TRC and the digitized stem and the relative sizes of the three sides of the RPP.

In Figure 5 is shown the segment of the primary branch. Again, a TRC of base radius unity is located at the origin, parallel to the z-axis, to form the stem section. Copies of the prototype secondary branch are attached in the neighborhood of a node (or nodes) whose location(s) is given as input. For each copy three orientation angles must be given: the polar angle θ with the segment stem, the azimuthal angle ϕ, and the rotation ψ around the secondary branch axis. Also given for each copy is a magnification (tantamount to a base radius for the secondary branch). The number of branches per node and the number of nodes per segment are given as input. Because the stem TRC will be connected to another TRC, in the next stage, it is capped with a sphere to soften the probable discontinuity.

The primary branch, shown in Figure 6, consists of a stem TRC, described as above, and one or more copies of the segment attached heel to toe. The three orientation angles must be given for each copy but the magnifications are determined by the requirement that the base radius of the copy TRC must be equal to the upper radius of the previous TRC to which it is attached. The vertex of the copy TRC is located (by the code) at the vertex of the spherical cap for the previous TRC. The number of such copies is given as input. A final copy of a secondary branch may be placed at the end with orientation angles given as input.

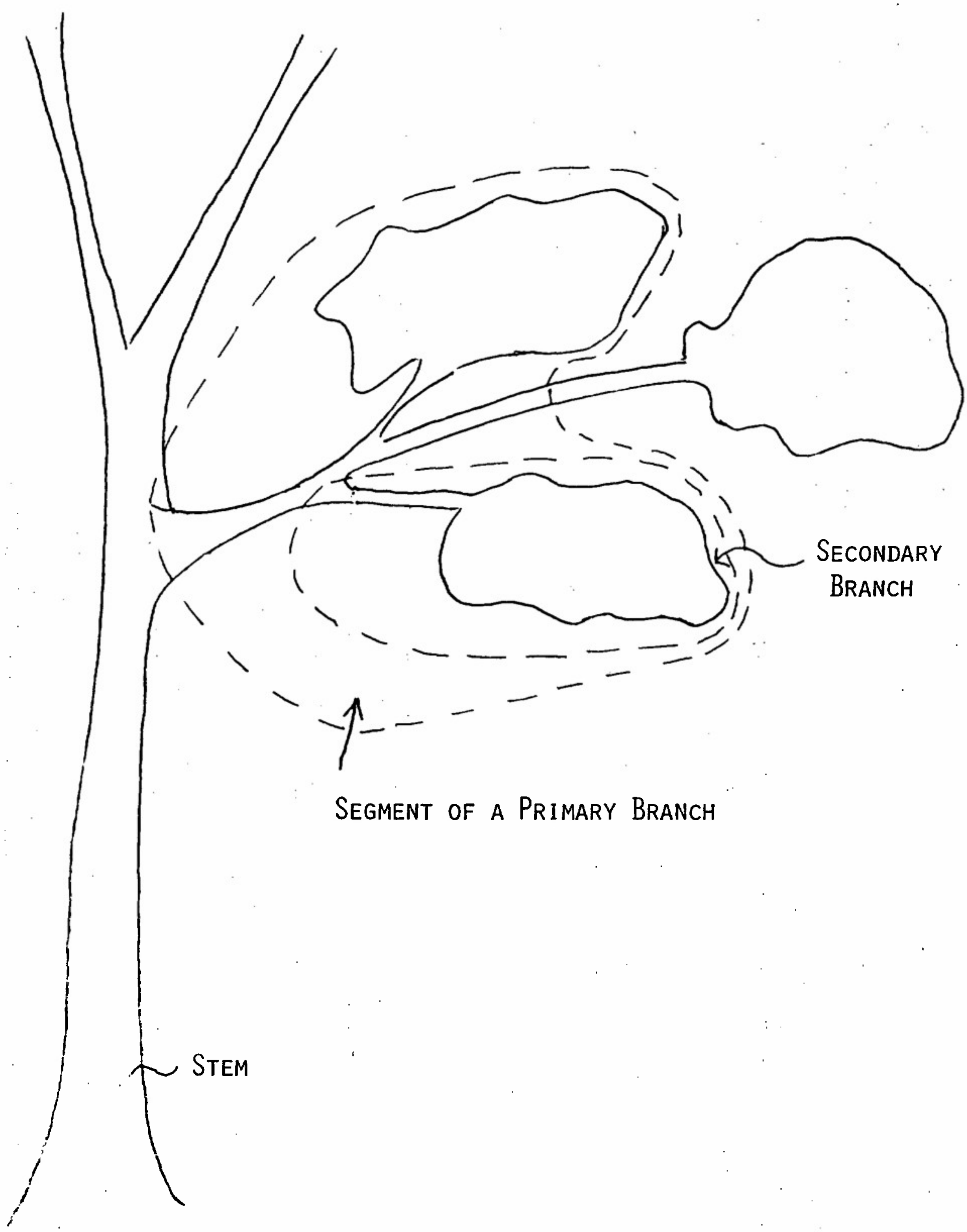


FIGURE 3: PROTOTYPE STRUCTURES FOR A TREE

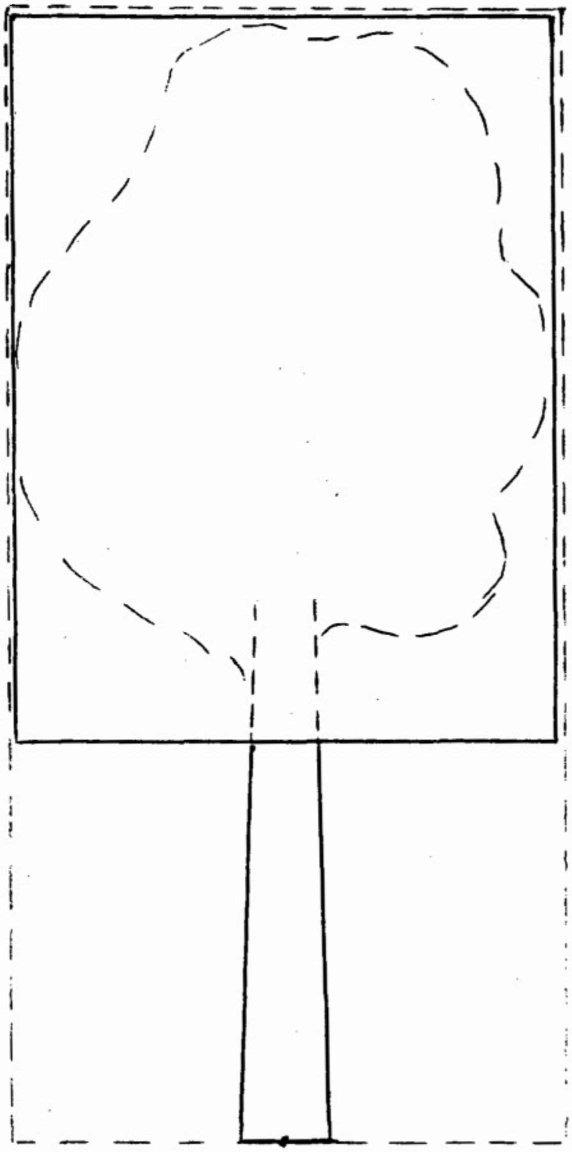


FIGURE 4: A SECONDARY BRANCH

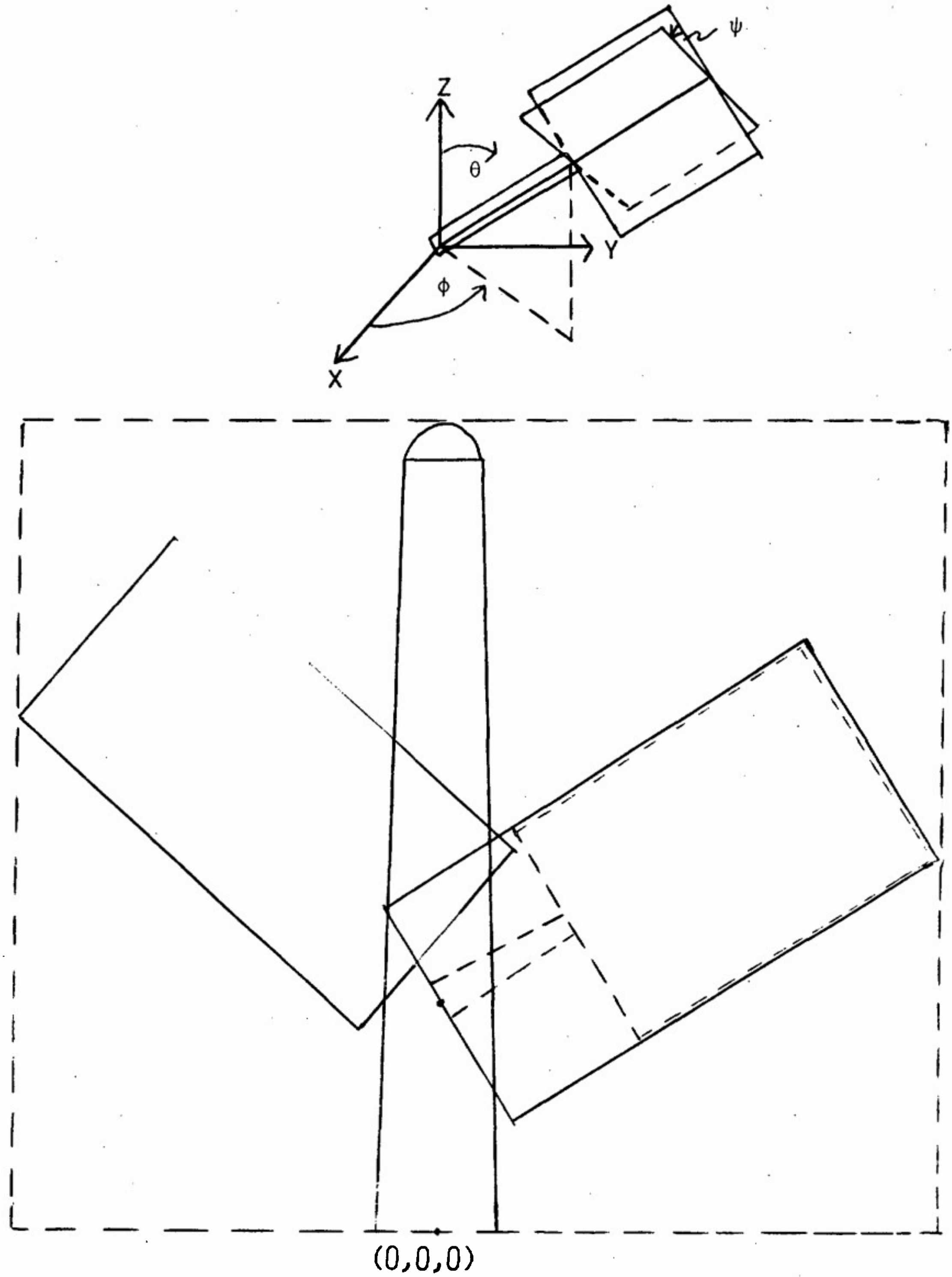


FIGURE 5. A SEGMENT OF A PRIMARY BRANCH

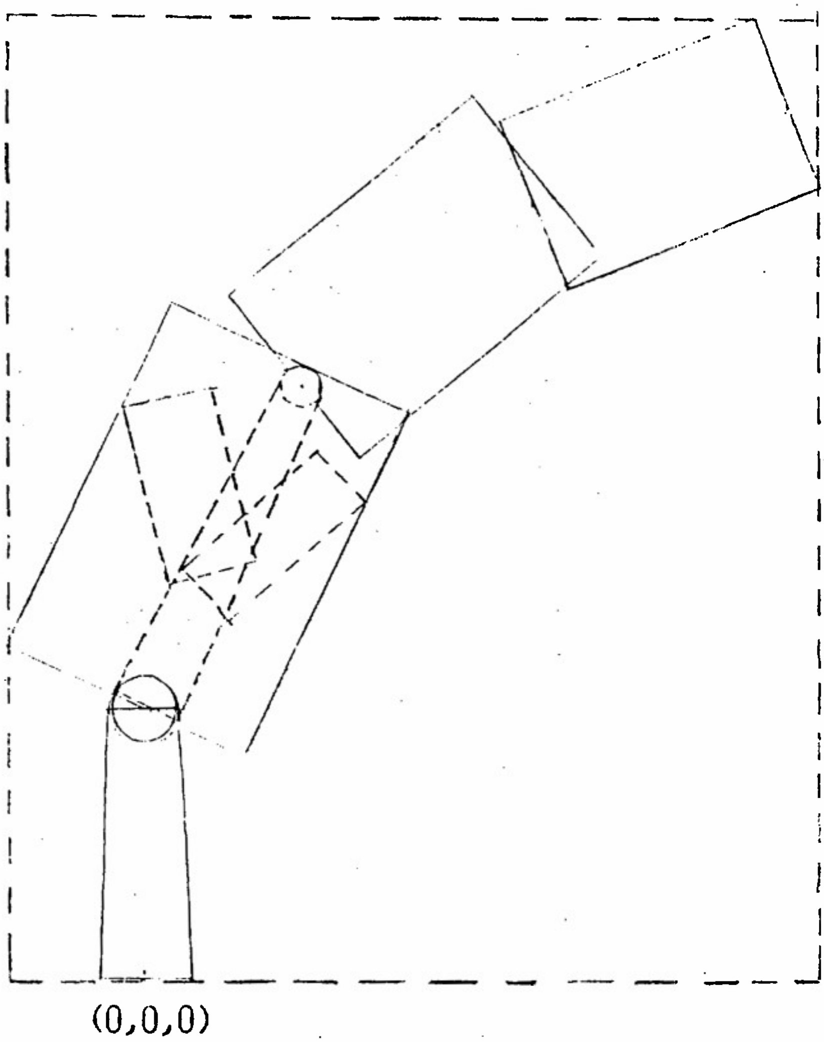


FIGURE 6: A PRIMARY BRANCH

The division of the primary branch into segments serves several purposes: 1) it allows an approximation to the curvature of a "typical" branch, 2) it limits the number of regions in a level of description and 3) it reduces the quantity of stored data.

The complete tree is constructed, as in Figure 7, of a series of TRCs, each capped with a sphere, and primary branches. The height and two orientation angles θ and ϕ are given for each TRC and joining radii are made equal. For each primary branch copy, a location vector, three orientation angles and a magnification are needed.

Because a complex tree may have as many as fifty odd regions in this last stage, an additional level of description is superimposed on that just described. It consists of a set of RPPs, each enclosing several of the regions. The degree to which these can be kept separate (non-overlapping) determines the effectiveness of the method. This point will be discussed further in the last chapter.

A complete bush can be constructed from either secondary branch copies or primary branch copies or a combination of these. The advantage of the primary branch in this construction is simply that more curvature can be given to the individual stems. For efficiency in tracking the secondary branch is superior.

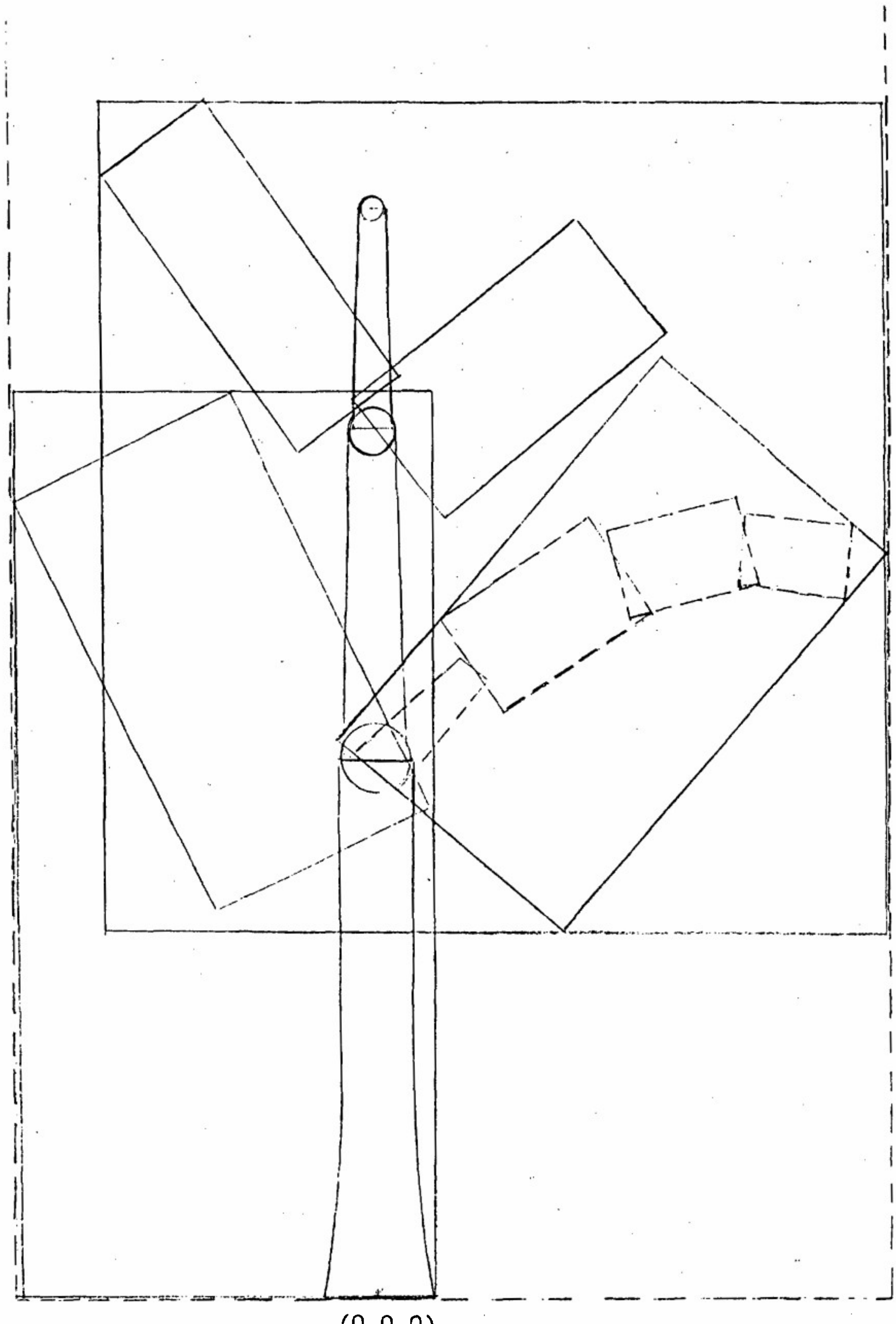


FIGURE 7: THE TREE

IV. THE LEAF AND TWIG STRUCTURE

Because the leaf and twig structure is far too complicated to be represented by combinatorial geometry bodies and regions, it was necessary to devise a special representation with compact storage and efficient tracking characteristics. The original plan, that of a "statistical leaf cloud", was rejected because realism in a motion picture requires a static description.

The description which has been devised and successfully implemented is to reduce the structures to either two-dimensional or three-dimensional grid patterns which are stored as digitized information during execution of the program. These patterns are the equivalent of regular arrays of RPPs and, as such, can be characterized and tracked to analytically with impressive savings in storage and time.

There is one leaf and twig prototype for each class of vegetation (various deciduous classes and coniferous classes). Other prototypes for the same class are generated by means of 3-way magnifications of the basic prototype and unique optical properties.

Optical properties tables must be devised for each of the prototypes. A grid element intersected by a ray gives an index to a table. The table contains $I \cdot J \cdot K$ elements where I, J and K are the number of grid elements in each dimension of the array. A total of 4000 regions can be accommodated by the program, with any values of I, J and K. For two-dimensional patterns K is equal to unity. In order to reduce core storage requirements the tables are stored in a packed format in BLOCK DATA. The packing is done in FORTRAN and puts 10 region indices into each word of core. Thus, the optical information table requires a maximum of 400 words.

The contents of an element of the optical properties table is essentially an index to a color and an intensity maximum or a signal indicating void. This information must be supplemented by an angle-dependent function (or table) to obtain the actual intensity associated with the ray.

The tracking within the leaf and twig prototype begins with the specification of a ray direction and its intercept on the surface of an RPP containing the structure. The next step in tracking is a transformation into the coordinate system of the prototype. For a three-dimensional pattern the analytic grid search technique is then invoked and leads to an ordered sequence of sets of indices of regions along the course of the ray. Each set of indices is used to retrieve a value from the optical properties table. The tracking terminates when a non-zero value indicates a hit.

Very regular three-dimensional patterns can be reduced to two-dimensional patterns by means of several projective techniques. As an example of one of these, consider the needle and twig structure of a simple conifer, as in Figure 8. This pattern possesses certain symmetry axes: the twigs themselves are symmetry axes

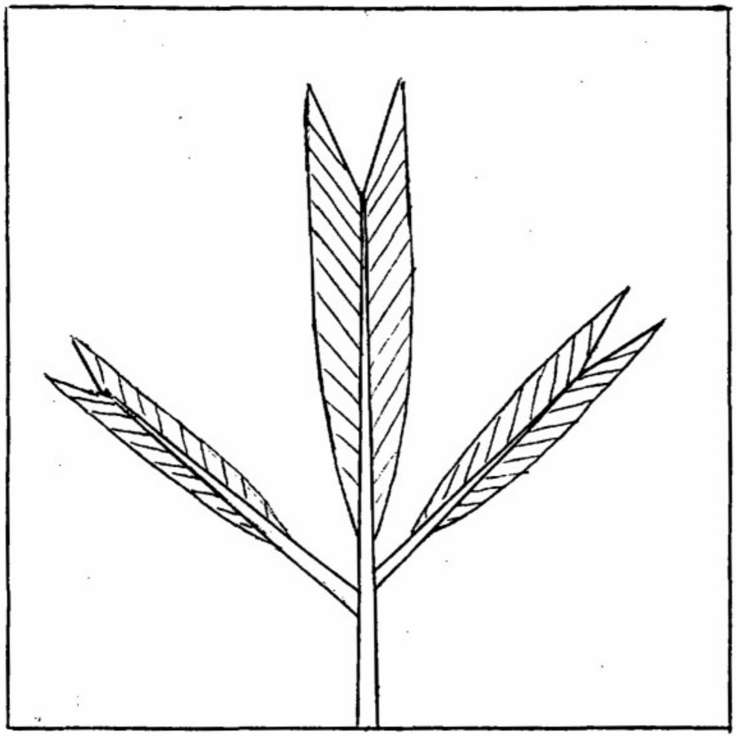


FIGURE 8: NEEDLE PATTERN FOR THE PINE TREE

for the needles. In tracking, the minimum distance of the ray to each of the twigs is determined to test whether the ray strikes within the needle envelope. A strike within the needle envelope will, with fixed probability, yield a reflection. The existence of a finite transmission probability allows preservation of the optical transmission of the collection of needles.

The pattern just described still has a certain two-dimensional quality which can be removed by a second projective technique. The single two-dimensional pattern can be made conceptually to exist on each of two mutually perpendicular planes. The nearest hit is the one recorded.

A third projective technique gives width to a two-dimensional pattern, essentially as in the second method described above, by projecting the pattern onto two mutually perpendicular planes with different lateral magnifications. An intersection of the ray with either of these planes yields a pair of indices (or a void signal) directly. An intersection with the third plane at x index I and y index J can be given an index which is a function of I and J but does not exceed IMAX=JMAX.

To recapitulate, this digitized representation of the leaf and twig structure has been chosen because:

a) for motion pictures, it maintains the geometric relationships and visual hues required by human perception; and

b) it allows compact storage and efficient tracking for a very complex structure.

V. DATA FOR THE TREE MODEL

A. Basic Philosophy

The basic philosophy underlying the model and the treatment of data was suggested by a few transparent observations on tree growth habits.

The first is that the geometry of a tree, although very complex, reveals several repetitive structures: leaf patterns, secondary branches, primary branches and even subdivisions of these entities.

Secondly, the parameters giving the relative size and orientation of these structures can depend on the location on the support system, i.e, axial position and azimuth.

Finally the aforementioned parameters fluctuate about their mean values so that the prediction of size and orientation is in part statistical.

We have already described, in Chapter III, the construction formalism which is based on the repeated structure or prototype. Here we are concerned with the specification of data on input and with the methods and results of processing these data. The ultimate input to the tree construction routines must be data for the TRCs forming the woody structure, and magnifications, displacement vector and rotation angles (3) for specifying each copy of a prototype.

With these observations and objectives as guidelines, four types of parameters were identified: constants, independent variables, dependent variables and statistical variables.

1. Constants

Inherent in the use of prototypes is the assumption of constancy for certain relative sizes and orientations. For example, the secondary branch is constructed once for each tree. Hence the relative size of base TRC and leaf structure is fixed, as is the taper of the TRC. In practice the height of this TRC and the taper factor are inputs (or resident information) and one lateral magnification of the leaf structure is adjusted so that the stem radii are continuous across the junction for that dimension. The other magnifications are input. Clearly these parameters must represent averages for secondary branches of the tree.

Similar remarks can be made about the segment of the primary branch and the primary branch itself. The ratio of height to base radius and taper factor for the base TRCs are determined by single input numbers (for each). The mean joining angles for the segments of the primary branch are chosen to approximate the curvature of an average primary branch, and these are constants for a particular tree. The number of nodes per segment and the number of branches per node will, for most cases, be given as constants.

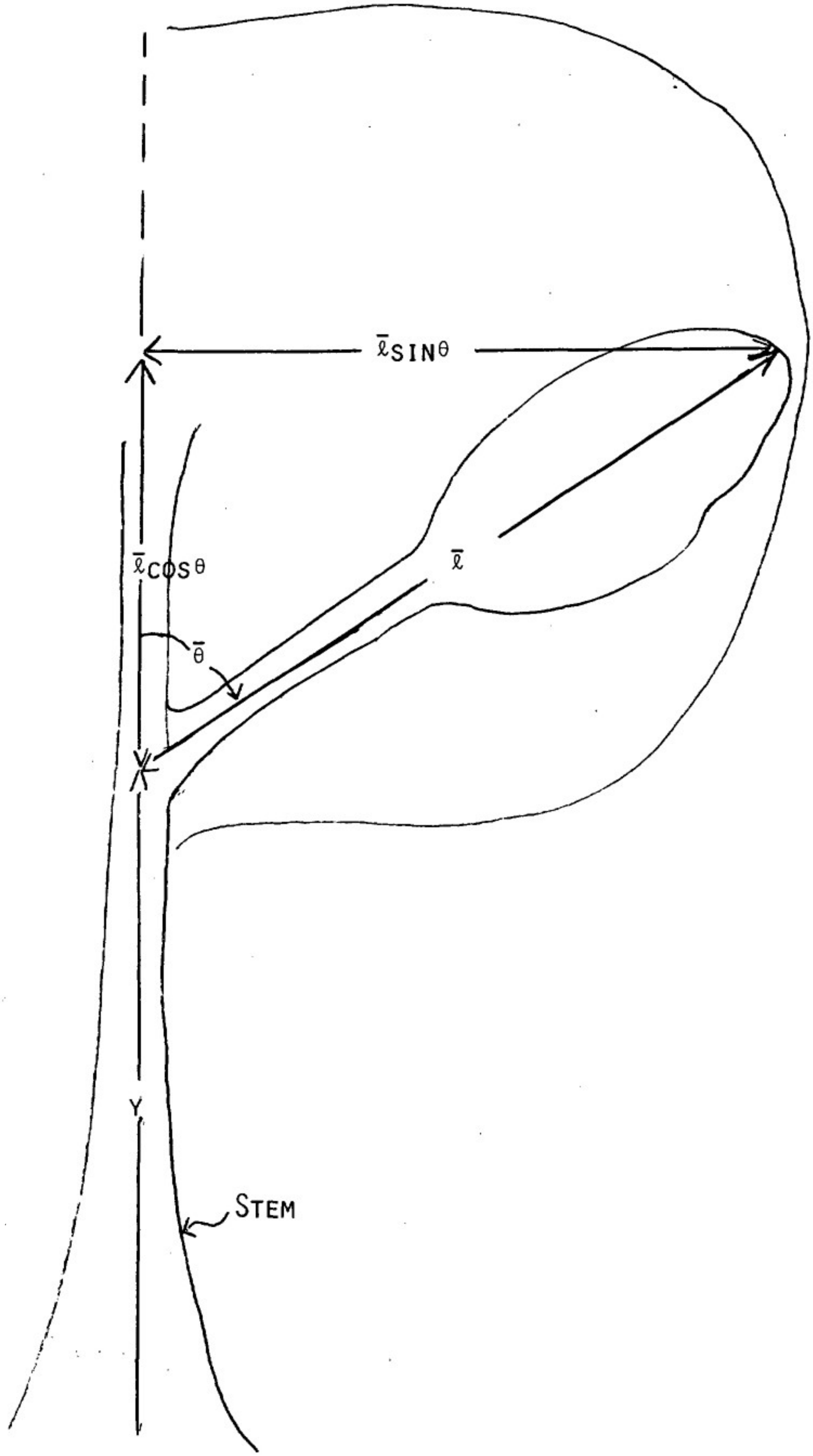


FIGURE 9: MEAN VALUES OF TREE PARAMETERS PRESERVE CROWN SHAPE

For the complete tree certain inputs are also constant: the total axial length, the mean position of the first node and the mean inter-node length.

2. Independent Variables

The relative height (or, for a branch, the axial position) of origin of the structure and the azimuthal angle about the axis are treated as independent variables. The actual values of these variables may be picked from distributions; once chosen they influence the determination of other variables for the same structure. Specifically, the displacement vector which places the base of a secondary branch on a stem of a primary branch and the azimuthal angle ϕ which orients the secondary branch about the primary branch may be thought of as independent variables.

3. Dependent Variables

The parameters of the construction which may depend on the independent variables are essentially mean values of the magnification, $\bar{m}$, the mean polar branching angle, $\bar{\theta}$, and the mean rotation of the structure about its own z-axis, $\bar{\psi}$.

The functional dependence of these variables on the independent variables is currently being treated as quadratic. For example, the mean polar branching angle for relative height h, $\bar{\theta}(h)$, is given by

$$\bar{\theta}(h) = ah^2 + bh + c$$

where a, b, and c are constants characteristic of a particular species and are read as input.

The choice of the quadratic was based on the fact that this form covers a variety of patterns of dependence and is capable of producing a given crown shape. If any further justification is needed it may be pointed out that the quadratic may be used to approximate a more complex function. In any case, the function chosen is not an essential part of the logic of the program and can easily be replaced.

An example will clarify the use of the quadratic: Let the crown shape, shown in Figure 9, be given by specifying the horizontal half width, x, as a function of the vertical position z:

$$x = Az^2 + Bz + C.$$

If the branch whose tip is at height z originates at height y on the stem where the mean polar branching angle is $\bar{\theta}(y)$ then the mean length $\bar{\ell}$ must satisfy

$$\bar{\ell}\sin\bar{\theta} = A(y + \bar{\ell}\cos\bar{\theta})^2 + B(y + \bar{\ell}\cos\bar{\theta}) + C$$

which is a quadratic in $\bar{\ell}$. Now $\bar{\ell}$ is related to the prototype branch length ℓ_0 by

$$\bar{\ell} = \ell_0 \bar{m}(y)$$

where $\bar{m}$ is the mean magnification at height y. Thus by specifying $\bar{m}(y)$ and $\bar{\theta}(y)$ properly the given crown shape can be realized.

If the crown shape is asymmetric then the coefficients in the quadratic may be functions of ϕ. This asymmetry is common for specimens not growing in isolation.

A few words should be said here about the use of the taper factor in determining the upper radius of the TRCs for the secondary branch, the segment of the primary branch, the primary branch and the tree stem. That the ratio of the upper to lower radius should be a decreasing function of the length of the TRC is clear. We were guided in the choice of function and the values of the taper factor by reference 3. The function used was

$$(R_2/R_1) = (L/R_1)^{-TPR}$$

where R_1 and R_2 are lower and upper radii, respectively, L is the length and TPR the positive taper factor with values between 0.10 and 0.14 for the tree stem, smaller for primary branches and smaller still for secondary branches.

Other data collections which were consulted in support of this effort are listed in references 4-6.

4. Statistical Variables

The actual values of the parameters whose mean values are obtained from distributions or from functional dependence on the independent variables are treated as statistical variables. Small ranges of variation about the mean are specified and values are obtained by random selection in this range.

In the example of the preceding section, y, the location of the base of a primary branch and ϕ, the azimuth of the branch, are both selected from probability distributions by means of stratified sampling. Once y and ϕ are known $\bar{\theta}(y,\phi)$, $\bar{m}(y,\phi)$ and $\bar{\psi}(y,\phi)$ can be determined. A relative range $\varepsilon(<<1)$ is specified for each variable and an absolute range is obtained as a product of ε and the mean value. Thus

$$\delta = \varepsilon \cdot \bar{\theta}(y)$$

gives a range centered at $\bar{\theta}$ within which θ can be selected.

B. Present Status

The programming and debugging of the input processor was not completed in time to generate data for the sample trees which will be discussed and demonstrated in Chapter VII. It was therefore necessary to produce a simple processor which would read data closely related to the bodies of the final constructions, thus bypassing the more sophisticated techniques for computation of means and random selection. The sets of data that were used will be discussed in Chapter VII.

It is presently planned that the input processor (which is now in the debugging stage) will be completed as a stand-alone program which will produce data in the form of that which was produced by hand for the sample trees.

VI. ORGANIZATION OF THE PROGRAM

A. Introduction

The generation of SynthaVision pictures requires three steps, the first and longest of which is the geometry and ray tracing step. The second step associates colors with regions and the third utilizes the SynthaVision hardware to produce a photograph.

The process is documented in the skeleton flowchart of Figure 11, where the main programs for each step and some of the subprograms for the geometry pass are shown.

B. The Geometry Step

The geometry pass (MAIN) anticipates the ultimate function of the program in producing composite scenes from a variety of models. It thus provides for the reading and processing of 1) vegetation data (TREE), 2) camouflage net data (INPACK,INSTAL)[7], 3) BRL-COMGEOM inputs (GENI). Each input is stored as a prototype, a copy (or copies) of which can be placed in the right position and the right attitude with the right magnification in the composite scene by means of transformation data. The number of copies and the nature of each is deduced from input to the main program. A signal is stored with each copy to invoke the appropriate ray tracing techniques.

After the geometry data have been processed and stored, MAIN calls the subprogram PICTUR which is responsible for producing a magnetic tape compatible with the SynthaVision process. This tape associates with each point on a picture grid the number of a region and an intensity level.

The picture grid is in the focal plane of a simulated pinhole camera and the association of object region number with grid point is made by a ray passing uninterrupted from object region to grid point (and from object region to source, although the source ray has not yet been activated). The intensity level is determined from the angles made by the normal to the surface of the object with the rays to camera and source.

PICTUR calls the subprogram CAMERA to set up the camera position, direction, focal point, focal plane and the picture frame in response to input. The picture grid is characterized by a maximum index and a cell-size for each dimension. The special scanning techniques for this grid will be described in Part D of this section.

PICTUR calls the subprogram INDEX to obtain a set of direction cosines for a ray. The ray is initiated from the focal point and is directed toward the object in the adjoint manner.

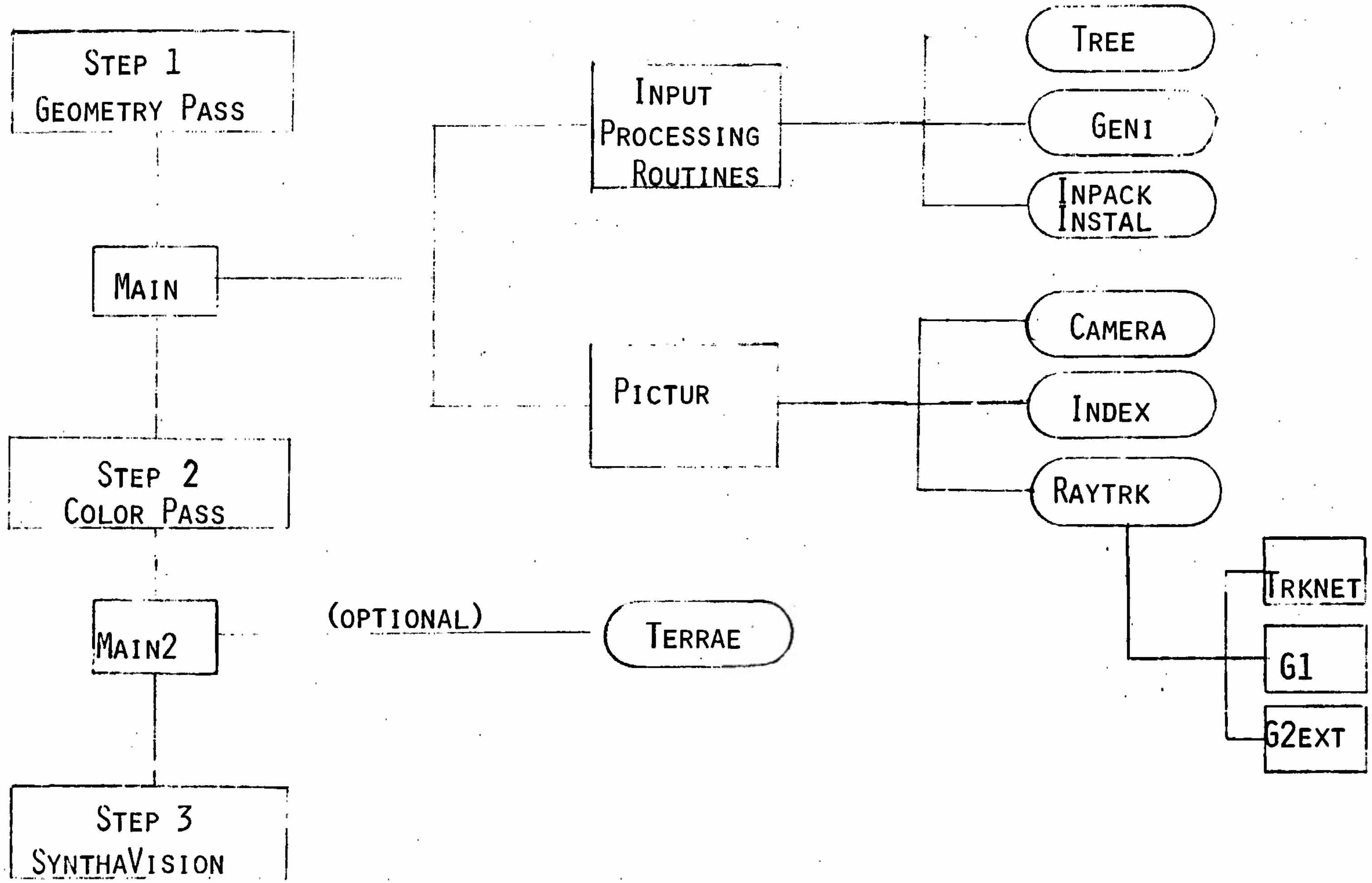


FIGURE 10: THE PICTURE-MAKING PROCESS

After initializing the ray, PICTUR calls the subroutine RAYTRK to govern the ray tracing for each ray. RAYTRK initializes the tracking by investigating the level of description that corresponds to the real world (see Figure 2). At each encounter with an RPP in this level RAYTRK determines the appropriate tracking techniques for the enclosed regions and calls the proper routines to pursue the ray to reflection by a real object or escape from that region set. The path from real object to source involves a change in direction cosines of the ray and an update of the initial position to the reflection point. RAYTRK then continues the tracking in the above manner until the source is reached or until another real object obscures the source.

RAYTRK calls the special tracking routine TRKNET for ray tracing to the camouflage net. For BRL-COMGEOM descriptions a modified and extended version of MAGI's CGPACK (not yet complete) will be used. Elements of the CGPACK are also used with the vegetation model, but the prototype-multi-stage method governs the use of these routines at all levels.

C. The Color Step

The color step consists in assigning to each region number a color code which corresponds to a set of intensity levels for the three primary colors. These levels are modified according to the intensity read from the geometry file. Three picture grids are then produced - one for each primary color. This information is then compressed and reformatted and stored on magnetic tape for the rest of the SynthaVision process.

The number of color codes (and therefore the number of hues) that are built into the color pass of the SynthaVision process is necessarily limited. An optional step (MAIN2 and TERRAE) permits the interpolation of these colors by spatial intermixing. This procedure is costly in that the system which drives the CRT display from which pictures are made must sense more information and therefore takes more time to produce the pictures. This interpolation scheme will shortly be replaced or supplemented by interpolation on the three intensity levels.

D. Special Scanning Techniques

The basic idea for the scanning of the focal plane of the camera is to spend most of the time ray tracing in portions of the picture where the greatest amount of optical information exists. Such optical areas comprise raster points in the focal plane where the probability is greatest that an examination of an adjacent raster point would yield a different color and/or light intensity. At places where the color/intensity is only slowly changing, the optical information is low, and PICTUR will spend proportionately less time scanning these regions. To achieve this an 8-fold logical scheme is employed.

In order to accommodate the logic for generating SynthaVision pictures, the number of horizontal and vertical raster grid points on the camera's focal plane is a multiple of eight.

The maximum number of grid points is 800 x 800. If the number of grid points specified in the input is not a multiple of eight, PICTUR truncates to the largest multiple of eight. PICTUR samples the picture plane by firing rays uniformly over the focal plane of the camera. These rays are fired from each point on a macro-raster grid, which corresponds to every 8th point of the picture raster grid. The information concerning the region hit, region number and reflected intensity etc. is stored. The macroraster grid then serves as a guide to the firing of additional rays.

The logic pattern is to test point by point the points of the macrogrid. If four adjacent points on the grid (I,J),(I+1,J), (I,J+1) and (I+1,J+1) have the same region IR and intensity, the assumption is made that all the intervening points in the picture would strike that region and have the same intensity. The picture grid is set to -IR for these points, the minus sign serves as a flag that the region was interpolated. In what follows, capital (I,J) indices refer to the macrorasters, lower case i,j refer to the picture grid. The possibility that other regions may be present within the macro region boundary is not considered until information about adjacent macro regions is available. At that time, a "touchup" pass is made, which fires additional rays as needed.

If all the adjacent macroraster grid points are not in the same region IR, then the macrogrid, which originally contained 8x8=64 picture grid points, is divided into four smaller areas by firing five more rays at grid points (i,j+4), (i+8,j+4), (i+4,j), (i+4,j+8) and (i+4,j+4). These areas are then four grid points wide in each direction. Each of these four areas is then tested in turn to see if the points which lie on the corners have struck the same region numbers and returned the same intensity. If so, all the points in the area are set to the same region number IR, with a minus sign as a flag. If not, PICTUR again divides the area into four smaller areas by firing rays through the grid points (i,j+2), (i+4,j+2), (i+2,j) and (i+2,j+2). PICTUR continues testing and firing additional rays in this manner until the picture grid is completed either by interpolation or by firing a ray through each grid point. Thus, PICTUR spends the greatest time sampling areas where the regions and normals are changing and interpolates where things are relatively constant.

A final "touchup" is then made to check for self consistency across the macrogrid boundaries. If all boundaries have been correctly handled, then all regions in the picture grid with a minus flag (indicating a filled in portion of the picture) should be only adjacent to points with the same region number (positive or negative). Positive regions may be adjacent to points with different (positive) region numbers. Additional rays are fired at any grid point where the above criterion is not satisfied.

VII. RESULTS

The methods described in the first six sections of this report have been applied to two tree types which we will refer to as a coniferous tree and a deciduous tree. Both were modeled on single local specimens. Dimensions and angles were estimated by eye rather than directly measured. For these reasons neither tree can be said to be typical of a given species. They are intended rather to demonstrate the method.

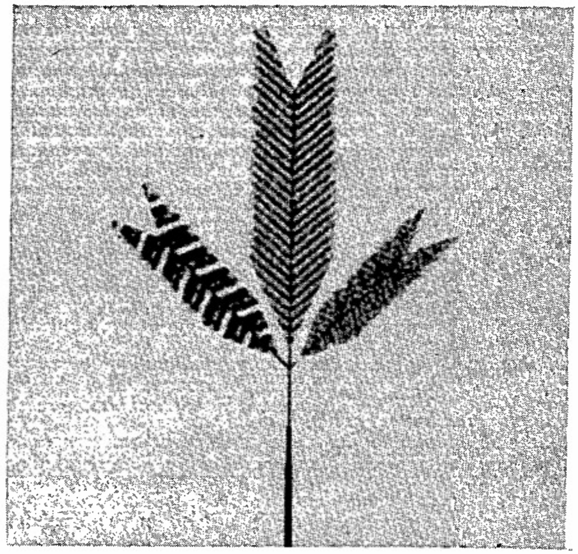
In Figures 11 through 14 are shown, in order, the stages of construction of the coniferous tree. Parameter values are given on the figures or in the accompanying tables. The symbol h denotes height for a TRC and axial position of copy base on the host TRC for a copy. No units are specified for h since the base radius of the base TRC is unity in each stage. The three rotation angles θ,ϕ,ψ, given in degrees, are defined in previous sections. Magnifications are denoted by the symbol m and are equivalent to base radius for the copy.

Figure 11 shows the needle clusters and twigs (digitized) attached to a stem (combinatorial geometry TRC) to form a secondary branch.

A segment of a primary branch of the conifer is shown in Figure 12. It was formed by attaching four copies of the secondary branch to points on the stem TRC in the neighborhood of the halfway point. Azimuthal angles were chosen in the neighborhood of multiples of 90° and polar angles were between 27° and 55°. The magnifications were chosen between 0.24 and 0.28. This last was a poor choice; the final picture would have benefited considerably by a choice of magnifications that were larger by a factor of 2.

In Figure 13 a primary branch is shown. It was constructed from a stem TRC and three copies of the segment (Figure 12) with a copy of the secondary branch topping the structure. The magnifications of the four copies are controlled by the requirement that the joining radii be equal. Hence the whole structure is ultimately controlled by the taper factors for the stem TRCs. Here again the appearance of the tree would have been improved by smaller taper factors in these stages. The joining angles, chosen to give curvature to the branch (θ and ϕ) and to vary the appearance of the segments along the branch (ψ), can be read on the table accompanying the figure.

Figure 13 also serves to demonstrate the resolution problems that arise for very fine structure. The apparently missing stems for secondary branches were simply too thin to be detected at the resolution of this picture (700 x 700). A higher resolution might have picked up some of this detail, but was hardly warranted. If such structure is important it can be detected at low resolution by enlarging the dimension and reducing the reflectivity proportionately. The problem occurs with greater frequency on the complete tree because of the necessarily smaller magnifications.



TRC HEIGHT = 35.0 R_2 = 0.65
NEEDLE-TWIG STRUCTURE: UNIT MAGNIFICATION
ALL SIDES

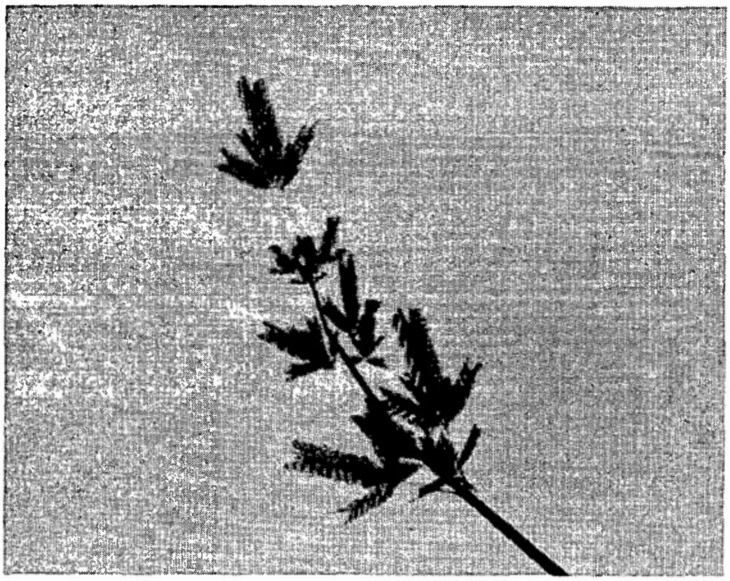
FIGURE 11: THE SECONDARY BRANCH OF THE CONIFER

TRC HEIGHT = 38.0 R_2 = 0.63

SECONDARY BRANCH COPIES

COPY #	h	θ	φ	ψ	m
1	18.7	52.0	85.0	5.0	0.24
2	18.5	27.0	190.0	-5.0	0.26
3	19.0	55.0	270.0	7.0	0.24
4	18.0	30.0	350.0	-5.0	0.28

FIGURE 12: SEGMENT OF A PRIMARY BRANCH FOR THE CONIFER



TRC HEIGHT = 18.0 $R_2 = 0.70$

SEGMENT COPIES AND SECONDARY BRANCH COPY*

COPY #	θ	φ	ψ
1	0.0	180.0	10.0
2	15.0	185.0	-10.0
3	30.0	190.0	20.0
4*	30.0	190.0	-15.0

FIGURE 13: PRIMARY BRANCH FOR THE CONIFER

Figure 14 depicts the complete conifer. There are 7 TRCs whose lengths and joining angles are given in the accompanying table. The upper end of each of the first 5 TRCs was chosen as a node and 4 primary branch copies were distributed about each node. Distributed about the node at the upper end of the 6th TRC are four secondary branch copies. The 7th TRC is topped by a single secondary branch. The angles and magnification and the position on the host TRC are given for each copy in Table I. It can be seen that mean magnification and mean polar branching angle decrease with height but are independent of azimuth.

The total number of bodies and regions that had to be stored for the conifer, including copy outlines and enclosing RPPs was 61. The computer time on the IBM 360/65 for a 500 x 500 picture grid was 91 minutes, but essentially the same results could have been obtained with a 250 x 250 grid and a running time of 23 minutes. The higher resolution was used to establish the fact that the missing structure was in fact the result of a resolution problem rather than a bug in the program.

Figures 15 through 17 are photographs of the deciduous tree in various stages of construction. The secondary branch is shown in Figure 15 and consists of a leaf and twig structure (digitized) atop a stem TRC.

The primary branch differs from the segment stage only by the addition of a base TRC. Only the primary branch is shown here. In Figure 16 three secondary branch copies are located on the upper of two TRCs. The two larger copies at the upper end of that TRC are used to create a bifurcated branch. The joining angles for branches and TRCs are used to give curvature to the branch. All parameters are given in the table.

The complete deciduous tree is pictured in Figure 17. Four TRCs and 31 primary branches were used. The axial distribution of branches for the model was more or less continuous. The mean magnification used was independent of axial position but varied "statistically" in the range 0.14-0.22. Mean polar branching angle is a decreasing function of axial position but independent of azimuth. Table II contains the data for this stage.

The deciduous tree required 72 bodies and 72 regions for its description. The picture of Figure 17 represents a 500 x 500 grid and took nearly three hours of running time on the IBM 360/65. Again, essentially the same detail would have been achieved with a 250 x 250 grid and about 45 minutes of running time.

It seems clear from the foregoing that the method is capable of realistic simulation of vegetation of various types and that the use of prototypes and digitized leaf and twig structures has been successful in compacting storage. On the other hand, the multi-stage method, intended to conserve running time, has not been used to its full potential. This has to do essentially with the very considerable overlap of enclosing structures (RPPs and BOXES) in the last stages of construction. The overlap reduces the effectiveness of the method by forcing the examination of large numbers of bodies along the ray. A solution to this problem will be developed in the next section.

TABLE 1. TRC's AND ASSOCIATED PRIMARY BRANCH COPIES FOR THE CONIFER

TYPE	No.	h	θ	φ	ψ	m
TRC	1	6.0	0.0	0.0		
COPY	1	6.0	65.0	50.0	-5.0	0.22
COPY	2	5.8	62.0	130.0	10.0	0.19
COPY	3	5.9	67.0	220.0	5.0	0.21
COPY	4	5.8	60.0	315.0	0.0	0.22
TRC	2	4.0	5.0	5.0		
COPY	1	3.8	55.0	5.0	-5.0	0.20
COPY	2	3.9	60.0	100.0	10.0	0.19
COPY	3	3.8	57.0	190.0	5.0	0.20
COPY	4	3.9	62.0	275.0	0.0	0.19
TRC	3	7.0	0.0	0.0		
COPY	1	6.9	57.0	40.0	-5.0	0.19
COPY	2	6.8	50.0	140.0	10.0	0.18
COPY	3	6.9	52.0	235.0	5.0	0.18
COPY	4	7.0	55.0	325.0	0.0	0.17
TRC	4	8.0	-5.0	10.0		
COPY	1	7.7	45.0	0.0	10.0	0.18
COPY	2	7.8	52.0	85.0	5.0	0.17
COPY	3	7.7	47.0	180.0	0.0	0.16
COPY	4	7.9	50.0	265.0	-5.0	0.15
TRC	5	5.0	0.0	0.0		
COPY	1	4.9	45.0	45.0	0.0	0.15
COPY	2	4.8	40.0	145.0	10.0	0.16
COPY	3	4.9	47.0	230.0	-5.0	0.14
COPY	4	4.8	42.0	320.0	5.0	0.15

TABLE 1. PAGE 2

TYPE	NO.	h	θ	φ	ψ	m
TRC	6	8.0	-5.0	0.0		
COPY	1	7.6	15.0	10.0	5.0	0.04
COPY	2	7.8	20.0	90.0	-5.0	0.04
COPY	3	7.7	27.0	190.0	0.0	0.04
COPY	4	7.8	22.0	270.0	10.0	0.04
TRC	7	6.0	0.0	0.0		
COPY	1*	4.6	0.0	0.0	0.0	0.04

* SECONDARY BRANCH COPY

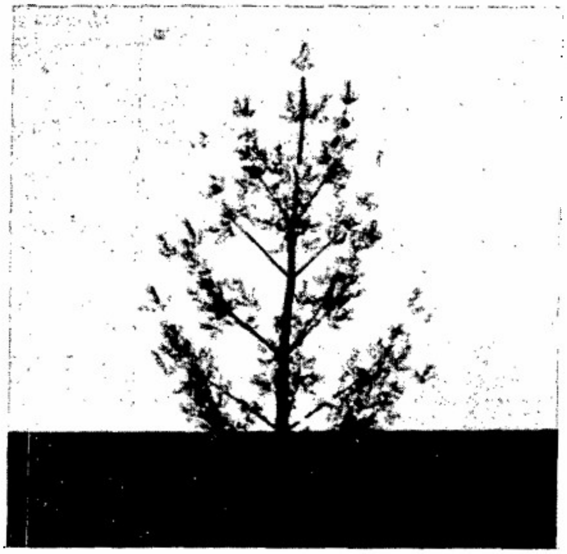


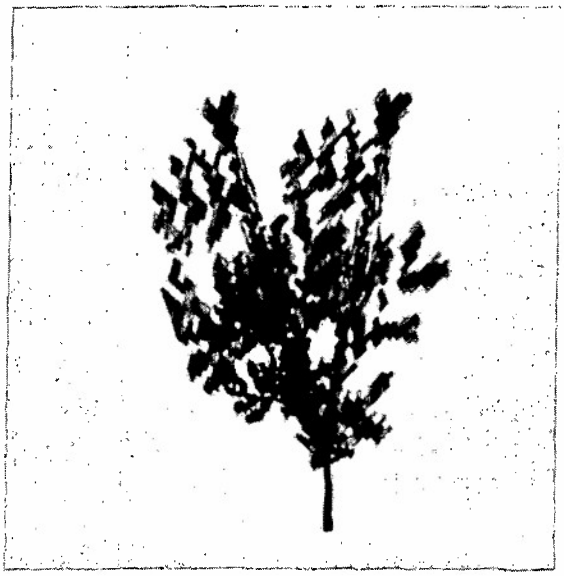
FIGURE 14: THE CONIFER. PARAMETERS ARE GIVEN IN TABLE 1.

TRC HEIGHT = 5.0 R_2 = 0.9

LEAF AND TWIG STRUCTURE MAGNIFICATIONS:

X:Y:Z = 1:2:3

FIGURE 15: THE SECONDARY BRANCH OF THE DECIDUOUS TREE



TRC and Secondary Branch Copies for "Segment Stage"

Type	No.	h	θ	φ	ψ	m
TRC	1	8.0	0.0	0.0		
COPY	1	8.0	15.0	80.0	-80.0	1.0
COPY	2	8.0	15.0	-86.0	90.0	0.8
COPY	3	4.0	35.0	-10.0	0.0	0.5
		TRC and Segment Copy for Primary Branch				
TRC	1	5.0	0.0	0.0		
COPY	1	5.0	10.0	0.0	10.0	1.0

Figure 16: Primary Branch for the Deciduous Tree

TABLE II. TRC's AND ASSOCIATED PRIMARY BRANCH COPIES FOR THE DECIDUOUS TREE

TYPE	No.	h	θ	φ	ψ	m
TRC	1	16.0	0.0	0.0		
TRC	2	6.0	5.0	0.0		
COPY	1	0.1	110.0	0.0	5.0	0.15
COPY	2	0.5	107.0	170.0	-10.0	0.20
COPY	3	1.5	105.0	85.0	-5.0	0.21
COPY	4	1.7	105.0	270.0	0.0	0.18
COPY	5	2.8	100.0	55.0	-5.0	0.18
COPY	6	3.0	102.0	225.0	-5.0	0.21
COPY	7	4.6	95.0	145.0	0.0	0.20
COPY	8	4.4	93.0	325.0	10.0	0.18
COPY	9	5.8	90.0	0.0	10.0	0.20
COPY	10	6.0	88.0	180.0	5.0	0.21
TRC	2	6.0	-5.0	90.0		
COPY	1	1.7	85.0	90.0	-5.0	0.22
COPY	2	1.3	86.0	260.0	0.0	0.22
COPY	3	2.9	80.0	50.0	7.0	0.20
COPY	4	3.1	80.0	230.0	-10.0	0.21
COPY	5	4.7	75.0	115.0	-7.0	0.18
COPY	6	4.4	73.0	320.0	0.0	0.22
COPY	7	6.0	70.0	0.0	10.0	0.22
COPY	8	5.8	68.0	195.0	-10.0	0.17

TABLE II. PAGE 2

TYPE	No.	h	θ	φ	ψ	m
TRC	3	6.5	10.0	-10.0		
COPY	1	1.4	65.0	90.0	5.0	0.22
COPY	2	1.6	63.0	275.0	-5.0	0.18
COPY	3	3.0	60.0	55.0	10.0	0.22
COPY	4	3.2	61.0	225.0	7.0	0.20
COPY	5	4.3	55.0	135.0	-10.0	0.17
COPY	6	4.6	54.0	310.0	5.0	0.20
COPY	7	6.3	50.0	0.0	7.0	0.18
COPY	8	6.5	49.0	185.0	10.0	0.22
TRC	4	3.0	0.0	0.0		
COPY	1	1.5	45.0	85.0	12.0	0.18
COPY	2	1.6	46.0	280.0	5.0	0.20
COPY	3	2.9	30.0	45.0	15.0	0.22
COPY	4	2.8	30.0	200.0	-15.0	0.20
COPY	5	3.0	10.0	180.0	10.0	0.22

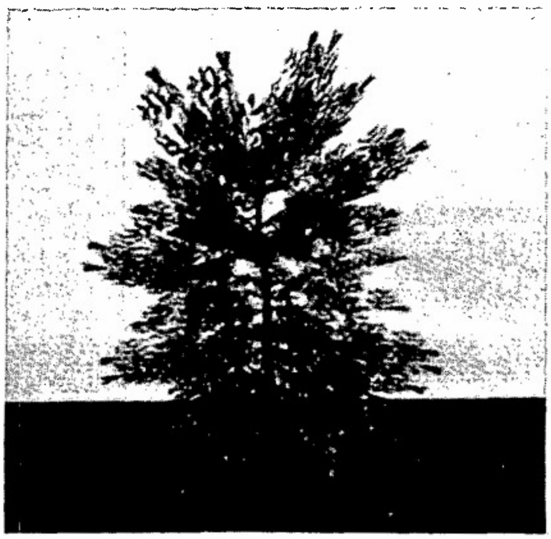


FIGURE 17: THE DECIDUOUS TREE. PARAMETERS ARE GIVEN IN TABLE II.

VIII. CONCLUSIONS

A. The Tree and Bush Model

It can be seen from the results described and demonstrated in the preceding section that the tree model is extremely promising. It is realistic in appearance and it is detailed enough to achieve a good approximation to the optical reflection properties of such a structure. In addition the requisite complexity is achieved with relatively small computer storage.

On the other hand the efficiency possible with the multi-stage approach has clearly not been exploited sufficiently. The source of the overlong running time is obviously the number of regions struck (and consequently investigated) in each level of description. This is a consequence both of the complexity of the object and of the very great overlap of structure in the final stages of construction. The remedy lies in a level of description of a particular kind, one which orders regions along the ray and displays little or no overlap.

Such a description technique is available and consists in superimposing on each of the complex prototype levels a regular array of RPPs which can be stored analytically and tracked in analytically. Only minor changes in tracking logic are required for this scheme but two additional algorithms must be developed. The prototype copies and TRCs of a given level must be associated with their containing RPPs and the analytic tracking scheme must be implemented for an array whose dimensions are determined internally. Much of the planning for these extensions has been performed already.

One feature of the tree and bush model has not been completed. This is the input processor which is in the final programming stages.

The proper use of the vegetation model requires both a data bank and experience. A few sources of compiled data have been referenced but these were found to be limited. Another possible source which is currently being investigated is the Hubbard Brook Ecosystem Study[8]. However, it seems certain that some additional field work will be required to obtain adequate information for any given species. Once the data are complete they must be analyzed and experimented with to provide the forms required by the model.

B. Terrain Models

It is intended that the camouflage net model, described and demonstrated photographically in reference 7, be used as a basis for simulating small and medium scale terrain elements, i.e., rocks or boulders and medium scale hills and valleys.

This model has been successful in describing a curved surface connecting points of given elevation and in assigning color distributions in such a way that efficient optical ray tracing is possible.

The essential features of the model which must be experimented with are the geometry, color and texture of the color patterns. This involves little or no programming. However, a necessary but trivial output of such a model is the vertical height of the surface for given horizontal position. This permits the location of other scene elements on the surface.

C. BRL-COMGEOM Inputs

The projected accomodation of BRL-COMGEOM descriptions within the framework of the extended MAGI CG package requires two additions to the package:

1. Input processing routines and tracking routines are needed for four BRL body types:

   a) the general ellipsoid (ELLG);

   b) the arbitrary polyhedron (ARB) in the several new input forms allowed by the GIFT code;

   c) the arbitrary surface (ARS);

   d) the torus (TOR).

Of these, (a) and (b) have been completed. Neither (c) nor (d) has been completed but both are underway.

2. A feature of the newest version of the BRL-COMGEOM as implemented in the GIFT code is that external air need not be defined. This is at variance with the requirements of the MAGI CG package: only if every region adjacent to a given region is defined can the "learning" process operate to limit the number of regions investigated at each intersection and thus to minimize running time.

Thus this type of BRL input requires either a technique for defining external air or a procedure similar to the GIFT program "equivalent RPP" method. This latter method finds and stores the smallest RPP enclosing each region. A search is initiated for each ray to determine which of the equivalent RPPs are intersected by the ray and only the associated regions are investigated. For the optical problem of interest here an ordering of the regions along the ray should be added.

At this writing no decision has been made between the two methods.

APPENDIX A: INPUT ORGANIZATION AND SAMPLE DATA DECK

1. Introduction

The input for the present vegetation code consists of two kinds of data:

a. Input to the tree generation routine for constructing the tree and for placing the copies of the tree in the real world;

b. Input to the camera routine to determine the origin and direction of the rays.

These data and the input formats will be described in detail below and will be illustrated by reference to Figure 18, which is a listing of the data deck used to generate the geometry tape for the deciduous tree of Figure 17.

In Figure 18 the right-most numbers are card numbers generated by the listing equipment and should not be confused with data. The card numbers will be used to reference specific cards in the deck in the discussion which follows.

2. Tree Generation Data

The tree is constructed in four stages and there is, therefore, a set of data cards for each stage of construction.

a. Stage Header Card

Each stage is introduced by a card bearing the stage number (1 through 5) and the number of bodies (truncated cones or prototype copies) used in that stage. This is illustrated by the cards numbered 1 (for stage 1), 4 (for stage 2), 9 (for stage 3), 12 (for stage 4), and 67 (for stage 5, the copy in the real world). The format is (2I5).

COLUMNS	CONTENTS
1-5	stage number, right justified
6-10	number of bodies, right justified

b. Body Cards

The cards for the TRCs and prototype copies of a stage follow the header card for that stage. All such cards have the format (A3, 3X, 8F8.3, 2I5). The information required depends on both the nature of the body and the stage it is in.

b.1. The Base TRC for Stages 1 through 4

For a base TRC (i.e., the first body for each of the first four stages), the code assumes that the center of the base is at the origin, that the height vector is along the z-axis, and that the base radius is unity. The resident taper factor for a stage is used to compute the upper radius. The required data are therefore:

COLUMNS	CONTENTS
1-3	TRC (alphameric)
47-54	H, ratio of height to base radius

b.2. Non-base TRCs of the Fourth Stage

All non-base TRCs are in the fourth stage and form the stem of the tree. They must be given in order, proceeding from the base to the top. The code assumes that the center of the base of each TRC is to be coincident with the end of the height vector of the previous TRC. The base radius of each TRC is computed as a fraction of the upper radius of the previous TRC. The resident fraction is presently 0.95. The required data are:

COLUMNS	CONTENTS
1-3	TRC (alphameric)
7-14	θ, polar angle of the height vector, in degrees
15-22	ϕ, azimuthal angle of the height vector, in degrees
31-38	H, ratio of the height of the TRC to the base radius of the base TRC.

b.3. Prototype Copies for Stages 1 through 4

The prototype copies all require essentially the same kind of data, except for those comprising the third stage. The data for a copy must follow the data for the associated TRC. Third stage copies must be in order starting from the base. The following description applies to all copies, except that the starred items are not required for the third stage:

COLUMNS	CONTENTS
1-3	COP (alphameric)
7-14	θ, polar angle, in degrees
15-22	ϕ, azimuth, in degrees
23-30	ψ, axial rotation angle, in degrees
31-38	*HC, location of origin along height vector of associated TRC
39-46	DM, magnification applied to the copy
71-75	stage number, right justified
76-80	prototype stage number

For a third stage copy, the location of the origin is supplied by the code as the upper end of the height vector of the previous TRC, i.e. either the base TRC or the TRC of the previous copy. The code checks the magnification to insure that the radius of a copy does not exceed the radius of the TRC at the point of attachment, reducing the magnification, if necessary.

b.4. Special Cards for the Fourth Stage

The cards interspersed among the fourth stage body cards and bearing a single integer N (columns 1-5, right justified) tell the code that the following N bodies are to be enclosed in an RPP for tracking purposes.

b.5. Leaf Structure Card

There is a special card required by the first stage to select the desired leaf and twig structure and to stretch it in three dimensions. This card (card number 3 in Figure 18) follows the TRC card and is in format (I5, 4F10.4).

COLUMNS	CONTENTS
1-5	IQ, reference number for a particular leaf and twig structure
6-15	FDX } For the containing RPP:
16-25	FDY } relative lengths of
26-35	FDZ } sides parallel to the x,y and z axes respectively
36-45	FJR } For the containing RPP: fraction of length in x-direction represented by the stem diameter.

FDX is actually superfluous and might as well be unity. FDY will normally be unity also to preserve roundness of the stem. However it can be seen that in the sample case FDY was chosen to be 2.0. FJR yields a scale factor on the three magnifications by joining the stem smoothly to the base TRC at its upper end. If a smooth joining is not of importance FJR may be altered from its true value to give any desired scale factor.

b.6. The Fifth Stage Copy

The fifth stage places magnified copies of the tree in given positions and orientations in the real world (the world of the camera). The required data are:

COLUMNS	CONTENTS
1-3	COP (alphameric)
7-14	DM, magnification
15-22	θ, polar angle, in degrees
23-30	ϕ, azimuthal angle, in degrees
31-38	ψ, axial rotation angle, in degrees
39-46	X } components of the new
47-54	Y } position of the
55-63	Z } origin.
71-75	stage number, right justified
76-80	prototype stage number, right justified

The prototype stage number will usually be 4, but any of the 4 prototype stages can be copied into the real world.

3. Input to the Camera Routine

Three cards are required by the camera routine in order to locate the observation point and to locate, orient and set the size of the picture plane.

The first of these cards, as illustrated by the card numbered 69, gives the position of the observation point and the direction of the ray through this point from the center of the picture plane. This ray is assumed normal to the picture plane. The format is (6F10.4).

COLUMNS	CONTENTS
1-10	X
11-20	Y — components of location of observation point
21-30	Z
31-40	WX
41-50	WY — direction cosines of central ray through observation point
51-60	WZ

The second card gives the data for the focal or picture plane. The format is (6F10.4).

COLUMNS	CONTENTS
1-10	F, distance along central ray from observation point to picture plane.
11-20	WH, horizontal width of picture plane.
21-30	WP, other lateral dimension of picture plane.

The final card of the deck gives the number of grid points in each of the two dimensions of the picture plane (see card numbered 71). The format is (2I5).

COLUMNS	CONTENTS
1-5	Number of grid points for horizontal dimension
6-10	Number of grid points for other lateral dimension.

	1	2								01
TRC							5.0	1		02
	2	1.0	2.0	3.0		0.035				03
	2	4								04
TRC							8.0	2		05
COP		15.0	80.0	-80.0	8.0	1.0		2	1	06
COP		15.0	-86.0	90.0	8.0	0.8		2	1	07
COP		35.0	-10.0	0.0	4.0	0.5		2	1	08
	3	2								09
TRC							10.0	3		10
COP		10.0	0.0	10.0	20.0	0.5		3	2	11
	4	36								12
	2									13
TRC							16.0	4		14
TRC		5.0	0.0		6.0			4		15
	2									16
COP		110.0	0.0	5.0	0.1	0.15		4	3	17
COP		107.0	170.0	-10.0	0.5	0.20		4	3	18
	2									19
COP		105.0	85.0	-5.0	1.5	0.21		4	3	20
COP		105.0	270.0	0.0	1.7	0.18		4	3	21
	2									22
COP		100.0	55.0	-5.0	2.8	0.18		4	3	23
COP		102.0	225.0	5.0	3.0	0.21		4	3	24
	2									25
COP		95.0	145.0	0.0	4.6	0.20		4	3	26
COP		93.0	325.0	10.0	4.4	0.18		4	3	27
	2									28
COP		90.0	0.0	10.0	5.8	0.20		4	3	29
COP		88.0	180.0	5.0	6.0	0.21		4	3	30
	1									31
TRC		-5.0	90.0		6.0			4		32
	2									33
COP		85.0	90.0	-5.0	1.7	0.22		4	3	34
COP		86.0	260.0	0.0	1.3	0.22		4	3	35
	2									36
COP		80.0	50.0	7.0	2.9	0.20		4	3	37
COP		80.0	230.0	-10.0	3.1	0.21		4	3	38

Figure 18: Data Deck for the Geometry Pass for the Deciduous Tree.

```
      2
COP    75.0     115.0    -7.0     4.7      0.18                                  4     3
COP    73.0     320.0    0.0      4.4      0.22                                  4     3
      2
COP    70.0     0.0      10.0     6.0      0.22                                  4     3
COP    68.0     195.0    -10.0    5.8      0.17                                  4     3
      1
TRC    10.0     -10.0             6.5                                            4
      2
COP    65.0     90.0     5.0      1.4      0.22                                  4     3
COP    63.0     275.0    -5.0     1.6      0.18                                  4     3
      2
COP    60.0     55.0     10.0     3.0      0.22                                  4     3
COP    61.0     225.0    7.0      3.2      0.20                                  4     3
      2
COP    55.0     135.0    -10.0    4.3      0.17                                  4     3
COP    54.0     310.0    5.0      4.6      0.20                                  4     3
      2
COP    50.0     0.0      -7.0     6.3      0.18                                  4     3
COP    49.0     185.0    10.0     6.5      0.22                                  4     3
      1
TRC    0.0      0.0               3.0                                            4

      5
COP    45.0     85.0     12.0     1.5      0.18                                  4     3
COP    46.0     280.0    5.0      1.6      0.20                                  4     3
COP    30.0     45.0     15.0     2.9      0.22                                  4     3
COP    30.0     200.0    -15.0    2.8      0.20                                  4     3
COP    10.0     180.0    10.0     3.0      0.22                                  4     3
      5     1
COP    1.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0       5     4
   0.00      500.0     30.0       0.0         -1.0        0.0
   1.0     0.13           0.13
   500   500
-
```

Figure 18: Continued

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